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A PROGRAM TO EVALUATE/IMPROVE INSTRUMENTATION AND TEST METHODS FOR ELECTROEXPLOSIVE DEVICE SAFETY QUALIFICATION

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DEPARTMENT OF THE AIR FORCE
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U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

FOREWORD

This program was initiated at the National Bureau of Standards in response to a request from the Aeronautical Systems Division (AFSC) of the Air Force Wright-Patterson AFB. Funding for the effort was provided by the Air Force (Contract No. F33615-72-5013). The general objective was to provide the Air Force with optimum test procedures, instrumentation, and test devices for qualification of weapon systems with respect to electroexplosive device (EED) safety. In particular, instrumentation was required to determine hazards to EED's on board aircraft flying in the vicinity of Safeguard radars.

Phase I of the effort was designed to investigate and evaluate existing instrumentation, test devices, and facilities while Phase II was concerned with optimizing instrumentation to meet Air Force needs. It was hoped that existing equipment could, with modification, be adapted for satisfactory use. As it turned out, none of the existing stray energy monitor devices were satisfactory and development of new devices was deemed necessary. It was decided by ASD that the primary need was for a go, no-go type stray energy monitor (SEM) which could be used in routine flight-line safety checks as well as in-flight tests.

This report is divided into two parts to describe the results of Phase I and Phase II. Each part is written as a separate paper for presentation at the IEEE International Electromagnetic Compatibility Symposium in New York on June 20-22, 1973.

A Phase III effort has been initiated for the purpose of developing instrumentation systems to yield quantitative information on EED safety at Air Force test facilities such as Eglin Air Force Base, Florida. The new instrumentation will employ solid state diode detectors to monitor both pin-to-pin and pins-to-case voltages when installed in a weapon system in place of EED's.

The report on Phase III will be issued separately following completion of the work in September, 1973.

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ABSTRACT

Adequate qualification of weapon systems for EED safety has been a long-standing problem in the military services. During the past 15 years various instrumentation, test devices, and methods have been developed with some success. In this report, available devices and instrumentation are evaluated with respect to sensitivity to low power levels, broadband response, ease of use, etc. This work is included in Phase I of the program.

In Phase II the objective was to develop a new go, no-go type stray energy monitor (SEM) with sensitivity in the tens of milliwatts range and response up to at least 10 GHz. A description is given of the new SEM which employs thin film fuses and monitors both pin-to-pin and pins-to-case hazardous voltages. Safety factors obtainable with the new device are in the 15 dB range relative to a 1 A, 1 W EED.

Key words: Electroexplosive device safety; electromagnetic compatability; electromagnetic interference; squib.

PHASE I

AN EVALUATION OF AVAILABLE STRAY ENERGY MONITORS FOR ELECTROEXPLOSIVE DEVICE (EED) SAFETY QUALIFICATION

1. INTRODUCTION

Electroexplosive devices (EED's) are used extensively by the military services, NASA and others to initiate functions such as bomb release, rocket motor firing, aircraft engine fire extinguishers, etc. The most common type of EED in present use is the hot bridgewire. In this device, a fine wire is heated by passage of an electrical current to a temperature high enough to explode a small charge in intimate contact with the bridgewire. This primary charge then initiates a larger charge which performs the desired function. The attractive features of hot-bridgewire EED's include the large force obtained from a small volume and the relative ease with which they can be controlled from remote locations.

Construction details of a typical hot bridgewire EED are shown in figure 1. Normal firing occurs when a source of electrical energy is connected across the pins and this is called the pin-to-pin firing mode. Firing can also occur when sufficient voltage (rf or dc) exists between the pins and the metal case which encloses the device to cause an arc. This is the principal pins-to-case firing mode. Another pins-to-case firing mode occurs when rf potentials cause dielectric-loss heating of the primary charge to its ignition temperature. A less well documented firing mode can occur when the header material is heated by dielectric loss due to rf potentials either pin-to-pin or pins-to-case. Heat generated in the header is conducted to the bridgewire causing

the primary charge to initiate. Measurements at 10 GHz indicate that for certain EED types, as much as 96 percent of the power absorbed by the EED goes into heating the header[1]. For this reason more investigation into this firing mode should be carried out.

Electroexplosive devices are usually rated in terms of their no-fire current. For example, a typical EED type has a 1 A no-fire current and this current is just below that which begins to fire a small number of devices in a large population. Typical 50 percent fire currents for this device is 1.3 A while the all-fire current may be 1.8 A. The latter is the current which will fire 100 percent of a given population with 95 percent confidence factor. In a weapons system, such a device would have approximately 5 A applied to its input pins to insure firing with a reasonable safety factor. The energy source is normally a dc supply or a capacitor discharge, and firing is initiated by means of a switch. Time to fire after application of power varies from a few microseconds to a few milliseconds.

Unfortunately, EED's are subject to unintended initiation caused by pickup of stray electrical energy by the EED and its associated circuitry. Sources of this stray energy include static charges, on-board rf sources (Avionics) in aircraft, external rf sources such as radar, lightning discharges, and switching transient pickup from adjacent wiring. A common cause of unintended initiations is incorrect or faulty wiring within the weapon or system (e.g., aircraft) [2].

It has become common practice for the military services and NASA to test new and/or modified weapons, aircraft, missiles, etc. for EED safety prior to deployment in the field. For the most part, these tests are designed to evaluate susceptibility to EED firing by stray rf energy.

Instrumentation and methods used for these tests will be described later in this report. Tests are also required on aircraft on the flight line prior to the loading of ordnance. These tests are somewhat simpler than the qualification tests mentioned above but are, nevertheless, very important. A major part of the flight line tests can be made with dc and low frequency instrumentation to reveal the presence of voltages at the EED jack or receptacle. To test for the presence of rf and microwave power, a device which responds to low levels of high frequency energy must be used. A single device which responds to static, low level dc, rf and microwave energy in both pin-to-pin and pins-to-case modes would be ideal. At present, no such device exists which yields the required 20 dB safety factor in all firing modes at frequencies up to 10 GHz. That is, the test device is required to respond to power levels 20 dB below that necessary to fire the actual EED, in any firing mode.

2. EVALUATION OF STRAY ENERGY MONITOR DEVICES AND SYSTEMS

During the past 15 to 20 years test devices and facilities have been developed to assess the susceptibility of weapon systems to the inadvertant firing of EED's. Test devices range from the go, no-go type (SEM piston actuator) to those which yield quantitative information (thermocouple instrumented EED's) as shown in the following list. Test facilities exist at Naval Weapons Laboratory, Dahlgren, Va., Picatinny Arsenal, New Jersey and Eglin AFB, Florida.

It is the purpose of this section of the report to describe and evaluate the various devices and facilities which now exist. In some cases the information upon which the evalutions are based was obtained by testing in NBS

laboratories. In others, information was obtained from the literature, discussions with knowledgeable people and observations at test facilities.

2.1. Temperature Sensitive Paints

So-called temperature sensitive paints are chemical substances which melt rather abruptly at a given temperature. The range of temperatures extends from 310K to 1640K and as many as 100 compounds, each of which corresponds to a discrete temperature, are available within this range.

To use these paints for stray energy monitoring, they are applied directly to the bridgewire of an EED from which the primary and secondary charges have been removed. Before applying the paint, the input lead-header-bridgewire assembly must be removed from the metal case. A small brush is usually used for the application after which the assembly is replaced inside the case.

After exposure, the assembly is again removed from the case and the bridgewire examined for "beading" of the paint which would indicate that the paint had melted. Both the paint application process and examination for "beading" must be done with the aid of a microscope. This is perhaps the most serious drawback to the use of temperature sensitive paints. Other factors which tend to limit their usefulness include ambient temperature variations which cause the power required to melt the paint to vary. Thus, the ambient temperature must be measured and corrections applied for ambients other than 295K.

The power required to melt a certain paint (#45) at a 293K ambient for various bridgewire sizes has been reported in the literature[3]. For a 0.3 A no-fire EED, the paint melted with 6 mW input yielding a 17 dB safety factor. On a

0.68 A EED bridgewire, the paint melted at 38 mW input for 11.5 dB safety factor. These are below the 20 dB factor specified by MIL-E-6051C.

Our overall evaluation is that temperature sensitive paints are at best of marginal utility for use by the Air Force. The reason for this is the extreme care which must be exercised in applying the paints to a bridgewire and in determining whether melting has occurred after exposure. In addition, they do not indicate hazardous pins-to-case voltages.

In specially designed devices these paints could be useful. For example, the paint could serve as a cement to hold down a small spring-loaded lever which is released when the paint melts and gives an easily read visual indication. Other similar designs are also possible.

2.2. Manganin Gage - Passive Technique for Measuring High Transient Currents

The manganin gage was developed at Lawrence Radiation Laboratory by Robert Parker in about 1969[4]. The device is designed to measure the energy in short electrical transients ($\int i^2 R\ dt$) from which the current can be calculated. It is fabricated from a thin tapered strip of metal (usually manganin) and is coated with a uniform layer of temperature sensitive paint. Typical dimensions are as follows:

width at narrow end	-	.0762 mm
width at wide end	-	.1524 mm
length	-	2.54 mm
thickness	-	0.127 to 0.0254 mm

A current pulse will cause heating in the taper and consequently melting of the temperature sensitive paint. By observing where the melt line occurs, one can determine the

energy in the pulse. An expression has been derived which provides a measure of the energy from simply measuring the distance to the melt line. This latter expression is:

$$R\int i^2 dt = \frac{d\ C_p h^2 \Delta T_u (a+ku)^2\ R\times 10^{-12}}{\rho}$$

where

$R\int i^2 dt$ = energy (J)

C_p = specific heat (Joule per kilogram Kelvin)

d = density (kilogram per cubic meter)

h = thickness of material (millimeters)

ΔT_u = melt temperature minus ambient (Kelvin)

a = width at narrow end (millimeters)

k = slope of taper

ρ = resistivity (ohm-m)

u = melt distance (millimeters)

R = total resistance of gage (ohms)

All terms in the right-hand side of the equation are known or can be easily measured. Therefore, the value of the integral can be determined.

The validity of measurements made with the gage is based on the assumption that the heating process is adiabatic, i.e., that no heat is lost to the surroundings. This assumption is valid for very short current pulses of the order of a few tens of microseconds. Used in this manner, the device is sensitive to relatively small amounts of energy. Values of energy for which the manganin gage is useful, range

from 0.273×10^{-3} Joule for a .0127 mm thickness unit to 2.2×10^{-3} Joule for a larger .0254 mm thickness unit. By comparison, the energy required to fire EED's ranges from 8×10^{-3} Joule for a Mark 1 squib to 257×10^{-3} Joule for the CCU-1/B ejection cartridge[5]. For many EED types, the average firing energy is in the range 20 to 100×10^{-3} Joule.

In terms of energy the manganin gage is 10 to 100 times more sensitive than typical EED's. However, this sensitivity is dependent upon delivery of the energy in a relatively short time interval. For example, it might be supposed that the device is useful for measurement of hazards from radar pulses which usually have durations from 1 to 10 μs. We can then compute the minimum power required using minimum energy value given above. That is,

$$P_{min} = \frac{E_{min}}{t} = \frac{0.273 \times 10^{-3}\ \mathrm{J}}{10 \times 10^{-6}\ \mathrm{sec}} = 27.3\ \mathrm{W}$$

for a 10 μs pulse and 273 W for a 1 μs pulse must be absorbed by the gage to yield a minimum reading. Radiated power densities sufficient to provide the above levels of power at the device input are not likely to be encountered at any reasonable distance from a radar.

In many respects the manganin gage is similar to an EED instrumented with temperature sensitive paint on its bridgewire as described in 2.1. above. For example, the cross-sectional area of the gage is .02 mm (.0762 mm × .0254 mm) at the small end which is approximately equal to that of a .0254 mm diameter bridgewire. The lengths are also comparable, 1.52 mm for the EED bridgewire and 2.54 mm for the manganin

gage. Both must be examined under a microscope to observe paint melt. For this reason and the fact that the manganin gage is designed for short, high current pulses, its use by the Air Force is considered marginal. It would, in fact, be less useful than a Mark I EED using temperature sensitive paint.

2.3. Thermocouple Instrumented EED's (TCI-EED's)

Thermocouple instrumented EED's are, at present, the most commonly used type of test device at military facilities. Originally developed by Denver Research Institute in the late 1950's, the device consists of an EED constructed with the usual bridgewire but without the primary and secondary charges. A thin film thermocouple is inserted into the back-end of the EED with the hot junction very close to the bridgewire. Removal of the primary charge from intimate contact with the bridgewire causes a change in the thermal properties of the device. In particular, heat loss is decreased and the time constant is increased so that the TCI-EED does not exactly simulate the thermal characteristics of the EED, but does simulate the electrical impedance with good accuracy. Barker and Fry[6] have calculated a thermal simulation factor, T/T', for instrumented and actual EED's and the value of this is generally of the order of 0.5 for the devices tested.

Heating of the hot junction is generally believed to be by means of heat conduction through the film of air separating the bridgewire and the junction. The cold junction is on the same substrate as the hot junction and hence ambient temperature changes have only a small effect on the thermocouple output. Details of the construction of the TCI-EED are shown in figure 2.

The junctions are usually bismuth-antimony and these metals yield a very high thermal emf. Thus, it is possible to detect input power levels far below (at least 30 dB) that required to fire a 1 A, 1 W, no-fire EED.

The thermocouple output is normally fed via wires to a suitable voltmeter or millivolt recorder. When performing rf tests, these wires can couple energy into the thermocouple and/or the structure in which the TCI-EED is located and cause inaccurate readings and/or burn-out of the thermocouple. This constitutes a drawback to the use of TCI-EED's. External thermocouple wires can be avoided by use of a miniature recorder which is small enough to be enclosed within the structure (pod, missile, etc.) in which the EED is located. Other means include converting the electrical signal to an optical one and coupling to external instrumentation via optical fibers and the use of voltage controlled oscillators to telemeter the information to remote recorders. Miniature recorders have been used successfully at Naval Weapons Laboratory while the fiber optics technique is used at Picatinny Arsenal.

Further limitations of TCI-EED's include the lack of capability for measuring pins-to-case voltages and a relatively large (up to 200%) rf-dc difference error[7]. This error arises due to coupling of rf energy from the bridgewire to the thermocouple. In the latter case, the energy coupled into the thermocouple causes circulating currents to flow in the hot junction resulting in much higher thermocouple emf's than for an equivalent amount of dc power in the bridgewire. (Prior to use, TCI-EED's are calibrated by applying measured amounts of dc power to the bridgewire.) While the rf-dc difference error is in the direction of greater safety, it could cause rejection of an otherwise

safe system. It should be noted that corrections can be applied for this effect because the increase is relatively slow and monotonic.

Measurement of the rf-dc difference for TCI-EED's constructed at Los Alamos Scientific Laboratory have been made at NBS and results are shown in figures 3 and 4. Note that the rf-dc difference increases with frequency. These measurements were made by recording the thermocouple output first with dc power input alone and then with 95 percent rf power and 5 percent dc power. The bridgewire temperature was held constant by adjusting the power to hold the bridgewire resistance constant. The 80-20 platinum-iridium bridgewire has an adequate temperature coefficient of resistance to allow precise measurement and control of its temperature.

To evaluate the TCI-EED as a stray energy monitor, it can yield accurate data for pin-to-pin firing hazards at dc and frequencies up to approximately 1 GHz. At higher frequencies the device is useful as an indicator of stray energy but uncompensated data is overly conservative due to rf eddy currents in the thermocouple and dielectric heating of the header. The magnitude of the error varies from unit to unit but may be as great as 200 percent. The perturbing effects of the thermocouple output leads which may couple to an rf field can be avoided at the expense of more complex instrumentation. Perhaps a suitable solution to this problem would be the use of carbon impregnated teflon leads which do not perturb the rf fields and hence do not couple to them. These electro-magnetically "invisible" conductors may, however, introduce some electrical noise into the measuring circuit.

2.4. Video Detector Instrumented EED's

The video detector was developed in order to overcome the low voltage output of the TCI-EED. Figure 5 shows such a device developed by R. J. Sons[8] at Sandia Laboratories. Note that this circuit is a voltage doubler with a balanced output. The output of the detector is almost 0.1 V for 1 mW input power while a TCI-EED with the same input power delivers only a few microvolts. However, TCI-EED output is electrically isolated from the input (except for some coupling above 1 GHz) while the video detector outputs are connected electrically to the input; complications may arise, especially in three and four pin EED's.

As shown, this diode detector is not designed to respond to pin-to-case voltages but it should be possible to develop a unit which is sensitive to pin-to-case potentials. The low frequency operation of the diode detector assumes that there is very little current drawn through the diodes. This implies that the diode load is a very high impedance amplifier and could lead to input noise problems, but this should not be considered a serious limitation. Of course as the frequency increases, more current passes through the junction capacitance of the diode and this causes the detector input impedance to drop. Since the dynamic diode resistance is higher than 10^4 ohms, the shunt capacitance begins to dominate the total diode impedance at frequencies above a few hundred megahertz and the effects of this loading will have to be evaluated.

Our tests have revealed one interesting fact that is often overlooked. When an EED is excited in the pin-to-pin mode, there exists some voltage from pins-to-case because some of the field lines terminate on the case. This means that any SEM designed to respond individually to both pin-to-pin and pins-to-case potentials will have an output from

pins-to-case when the unit is excited in the pin-to-pin mode. On the other hand, there should be no output from pin-to-pin when the device is excited in the pins-to-case mode. This is what is commonly referred to as common mode rejection. In order for any stray energy monitor to give a quantitative indication, it must be designed so that pins-to-case voltages do not affect the pin-to-pin measurement.

2.5. Piston Actuator Stray Energy Monitor

This type of SEM has a small piston which is highly visible if the power absorbed by it exceeds some value. As originally designed, the piston actuator was to have been a more sensitive replacement for the EED for test purposes. The intent was to replace the EED's with SEM's and operate the weapon system in the desired manner during a test. A quick visual inspection of the SEM's following a test would reveal the presence and location of unsafe conditions. Since the SEM is more sensitive than the EED (i.e., 0.1 W versus 1 W for dc power), there is a known minimum safety margin if the SEM does not actuate.

Test facilities which use these SEM's have had the experience that the SEM did not operate when the rf fields present were thought to be sufficient to cause SEM firing. The usual conclusion is that the SEM is not properly responding to the rf energy. NBS has conducted some careful tests to show that the net rf power required to fire SEM's is up to 8 times larger for rf power than for dc power. Figure 6 is a block diagram of the test setup used. The power absorbed by the SEM is the difference between the incident power and the reflected power as measured by the reflectometer and the two power meters.

The only assumption is that the test mount not absorb power. Care was used in the design of the SEM mount to make it as nearly lossless as possible. Figure 7 is a cross section view of the SEM in the mount which connects it to the normal 7 mm coaxial line. Note that the tapered outer and center conductors very nearly maintain a 50 ohm impedance while changing the size of the coax line down to the diameter of the SEM.

Since the mount has no observed resonances and there is nothing in the mount to absorb appreciable power, the difference between incident power and reflected power can be assumed to be the power absorbed by the SEM. The 0.3 dB accuracy of these power measurements is dependent upon the apparent directivity of the two directional couplers. The tuner located between these two directional couplers has the effect of greatly raising this directivity and in fact makes a tuned reflectometer.

Figure 8 shows the average power required to fire typical SEM's as a function of frequency. The firing power appears to peak between 6 GHz and 8 GHz at a level of approximately 0.8 W. Further tests showed that the SEM lead wires (pins), which are made of iron, absorb significant power in this frequency range. This has the effect of reducing the SEM firing sensitivity. The NBS data on SEM firing characteristics was obtained from firing 150 units.

Although there is uncertainty about the exact difference in firing power (safety margin) between the SEM and any particular EED at some arbitrary frequency, the SEM is usually more sensitive than EED's tested. The SEM exhibits a rather well behaved impedance characteristic over a wide frequency range but does not actually match an EED impedance.

Since the SEM does not match a particular EED impedance, the idea of using an EED as a test item has some merit. The secondary explosive is removed from the EED, leaving only the small primary explosive on the bridgewire. A safety margin is achieved by increasing the irradiation power by some known amount and checking for fired EED's.

Recommendations. The piston actuator and the modified EED's are useful test devices and could be used for in-flight testing and for testing after system modification to reveal gross effects such as shorts and wiring errors which would be overlooked by non-operational tests.

2.6. Flight Line Stray Energy Testers

There are situations on the flight-line where it is necessary to check EED firing leads for the presence of unsafe conditions. These conditions may be the result of worn insulation, corrosion, improper connection of wires, broken connectors, inoperative relays or short circuits to other wires. Typically, the firing circuits are short-circuited at all times prior to EED firing and the condition of this short circuit should also be checked.

Two prototype testers were built in 1961 by Denver Research Institute. The first unit is in some aspects the more sophiticated of the two and will be the one described in detail. Where there are significant differences in performance or operation between the two units, these differences will be discussed.

The tester using a ring modulator was designed to respond to dc voltage of either polarity and also to ac up to several hundred hertz. Calculations of the safe allowable energy in a firing circuit determines the gain and sensitivity

requirements for the tester. This energy is about 1/1000th of the marginal firing energy of the particular EED. Since these levels are low compared to the maximum no-fire current, it is apparent that stability rather than accuracy is the dominant factor. For this reason, the ring modulator is a good circuit to use since it can have sufficient sensitivity without the use of any preamplification. Figure 9 is a block diagram of the tester with the ring modulator.

The ring modulator is an ac diode bridge circuit whose 20 kHz output is zero at bridge balance. Any input current (ac or dc) will cause one pair of bridge diodes to conduct thereby changing their 20 kHz impedance in such a way as to cause bridge unbalance. The resulting 20 kHz signal is amplified, detected, integrated (approximately the same time response as the EED) and its level compared to the arbitrary unsafe level. If the output is large enough, a silicon controlled rectifier conducts through a lamp. Once fired, the SCR will continue to conduct until the circuit is intentionally opened by depressing the reset button.

The design criteria for the tester using magnetic amplifiers is similar to the ring modulator tester. The unsafe indicators are also similar. The primary difference is that the ring modulator accepts the stray energy directly while the mag-amp unit uses a thermocouple instrumented EED (TCI-EED) to convert the stray energy to a dc voltage which must be amplified. The choice of mag-amps is based on their stable zero point, gain stability, and ruggedness. The time response of the TCI-EED is such that overload protection is not normally fast enough to protect it. Therefore, the TCI-EED must be considered expendable. This might be a disadvantage. Another disadvantage is the need

for 400 Hz, 110 V power to supply the mag-amps. Without a converter of some type, the unit cannot be battery operated. The advantage is that the tester could be used for rf measurements as well as ac and dc.

Both units are designed to check the condition of the short circuit in the firing leads. Each tester supplies a test current through either the input resistor (ring mod. unit) or the heater of the TCI-EED (mag-amp unit). If the short is indeed present, there will be insufficient voltage to cause the indicator to function. This same current will serve to calibrate the unit when the leads are not connected to a short circuit.

The testers are relatively easy to use as the operator is merely required to connect two test leads to the circuit in place of the usual EED. The operator then selects the sensitivity by rotating the selector switch to the proper EED type. If there is a dangerous amount of stray signal present on the circuit, the no-go light functions. If the light does not function, the circuit is considered safe. The condition of the firing circuit is then tested by pressing one more button, the "Test Current" button. Again, an unsafe condition is indicated with a light, and a safe condition gives no light.

Other advantages of the tester include the following.

- The accuracy of the device is more than adequate for its intended use.
- The testers are provided with the means for self calibration.
- The indication of unsafe energy or unsafe circuits is positive and does not require interpretation by the operator.
- The units may be modified for any particular EED sensitivity.

The testers have certain shortcomings such as the fact that the ring modulator unit does not detect rf signals and neither of the units are suitable for in-flight use. Both units are designed to be used external to the weapon or aircraft; however, they could probably be used as in-flight testers with some modifications to the aircraft or weapon. Neither unit is completely free from some source of external power (batteries or dc to ac converter).

Recommendations. A perusal of selected accident reports indicates that some form of dc and low frequency pre-flight safety check would be desirable. Either of the DRI type stray energy testers could be very useful for this purpose.

2.7. Miniature Recorder for use with TCI-EED's

The thermocouple instrumented EED described previously requires some type of readout instrumentation. One type used at the Naval Weapons Laboratory (Dahlgren) is a photographic recording galvanometer. The dimensions are 127 mm in diameter by about 610 mm long and the unit can usually be located entirely within the larger weapons being tested. Up to 14 separate galvanometer movements can record simultaneously on the same chart. A smaller unit is also available for applications where space is limited.

The output from the TCI-EED is fed to a galvanometer winding which has sufficient sensitivity to deflect with very small currents (microamps or less). A spot of light reflects from a mirror located on each of the galvanometer movements and is focused onto the light sensitive chart paper. The chart is exposed during a measurement, after which it can be removed from the instrument and developed using a wet process. The sensitivity of the instrument is a function of the particular galvanometer movement chosen and usually decreases for the faster responding types. The response time of the galvanometers in use is 20-50 milliseconds.

The instrument is powered by batteries which are housed in a removable canister to simplify recharging. This power pack usually takes up more than half the total volume of the recorder.

In evaluating the recorder several favorable features were noted. The fact that the recorder yields a permanent record allows an evaluation of the input power to the TCI-EED as a function of time. The recorder can usually be located entirely within the weapon system being evaluated. Thus, there are no external wires to perturb or couple to rf fields. Also, instrumenting a weapon system does not require modifying the umbilical connector or weapon skin as is necessary when externally telemetering the data. It allows testing of relatively complex weapons systems having several EED's since the recorder can accommodate up to 14 recording channels.

A few undesirable features were also noted. The delay between the occurrence of the measurement and the availability of the data can be a serious shortcoming. Overload conditions, as well as insufficient signal conditions, can result in useless data. These situations do not become obvious until the chart has been developed. In smaller weapons there may not be sufficient room to locate the recorder. In this case the recorder must be located outside the weapon and this requires wiring between the weapon and the recorder. The need for developing the exposed chart by a wet process requires the availability of a processing facility. The use of galvanometers in the instrument requires that it be stable during a test. Thus, it is not suitable for in-flight tests.

The following recommendations are made for effective use of the recorders in EED testing.

- Acceptance testing--The recorder is well suited to initial qualification testing of relatively large weapons systems, such as the HERO tests. For this type of test, time, equipment, and qualified personnel are available to perform the large scale modifications necessary to install the recorder in the weapon system.
- Post modification testing--The recorder can be used in a few instances for testing a weapon system after a field modification. This is practical only when the recorder can be installed without additional modification to the weapon. Often in this situation, neither the time nor the equipment is available to mount the recorder.

2.8. Optical Readout for use with TCI-EED

Another type of readout instrumentation used with TCI-EED's is a system which uses an optical transmission link. Problems with the miniature recorder system described above include relatively large size, large power requirement and the fact that it is not real time. These limitations are mostly overcome with the optical system used by Picatinny Arsenal.

In this system, as many as 28 TCI-EED outputs are commutated and measured in sequence at a rate of 785 per second. The commutated thermocouple outputs are then applied to a sensitive voltage controlled oscillator(VCO). This voltage to frequency conversion obviates the need for stable dc amplifiers. The VCO output drives a power amplifier which in turn drives a light emitting diode(LED) at a frequency which is proportional to thermocouple voltage. The operations described thus far are accomplished inside the

weapon being tested for susceptibility. The total package is, however, smaller and requires less dc power than the miniature recorders.

The output from the LED is transmitted through a length of fiber optic tubing to an rf data telemetry link. The section of fiber optic tubing is a means of getting the thermocouple voltage information out of the weapon under test without disturbing the irradiating rf field or coupling rf energy into the thermocouple.

The telemetry receiver feeds information to both a magnetic tape storage and a video display. Observing the video display gives data in almost real time. This system would be used for the same type of testing as the miniature recorder system and requires nearly equal weapon system modification, etc. It would not normally be sensitive to vibration, however, and is typically smaller than the miniature recorder.

3. SUMMARY

There are several stray-energy monitor devices presently used for electroexplosive device safety testing. The National Bureau of Standards has evaluated some of these devices and has found that no single device is entirely satisfactory for all test situations. The following summary lists the most useful devices for three general test categories.

Type of Test	Useful Device	Comments
System Qualification and Acceptance Testing	TCI-EED	Quantitative output. No pins-to-case information. Errors increase above 1 GHz. Used with miniature recorders or fiber optic data output system.
	Video Diode	Needs further development.

Type of Test	Useful Device	Comments
Fly-by or Post Modification Testing	Piston Actuator	Go, No-Go. Possible uncertainty in safety margin due to rf impedance difference between SEM and EED. Decreasing sensitivity above 1-2 GHz.
	Manganin Gage	Useful for short pulse or transient signals.
	EED with Temp. Sensitive Paint	Repeated tests using different temp. ranges can estimate magnitude of stray energy.
Flight-Line or Post Modification Pre-Flight Test	Piston Actuator	Go, No-Go.
	Volt-Ohmmeter or Flight Line Stray Energy Tester	Good for finding wiring errors, faulty cables and relays, etc. DC to 30 MHz.

This list is to be used as a guide and not as justification for discarding any one particular test procedure or device in favor of another. Most of the test devices are useful in the right situation but can lead to erroneous conclusions when used beyond their capabilities.

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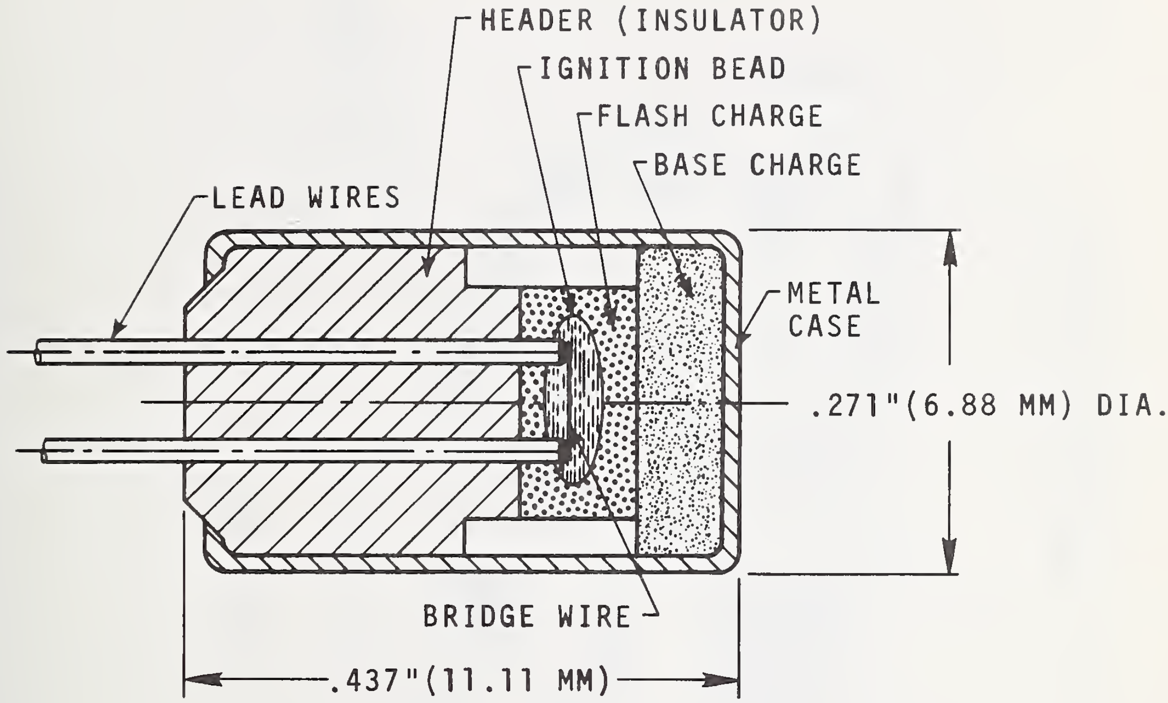


Figure 1. Section view of typical electroexplosive device (EED).

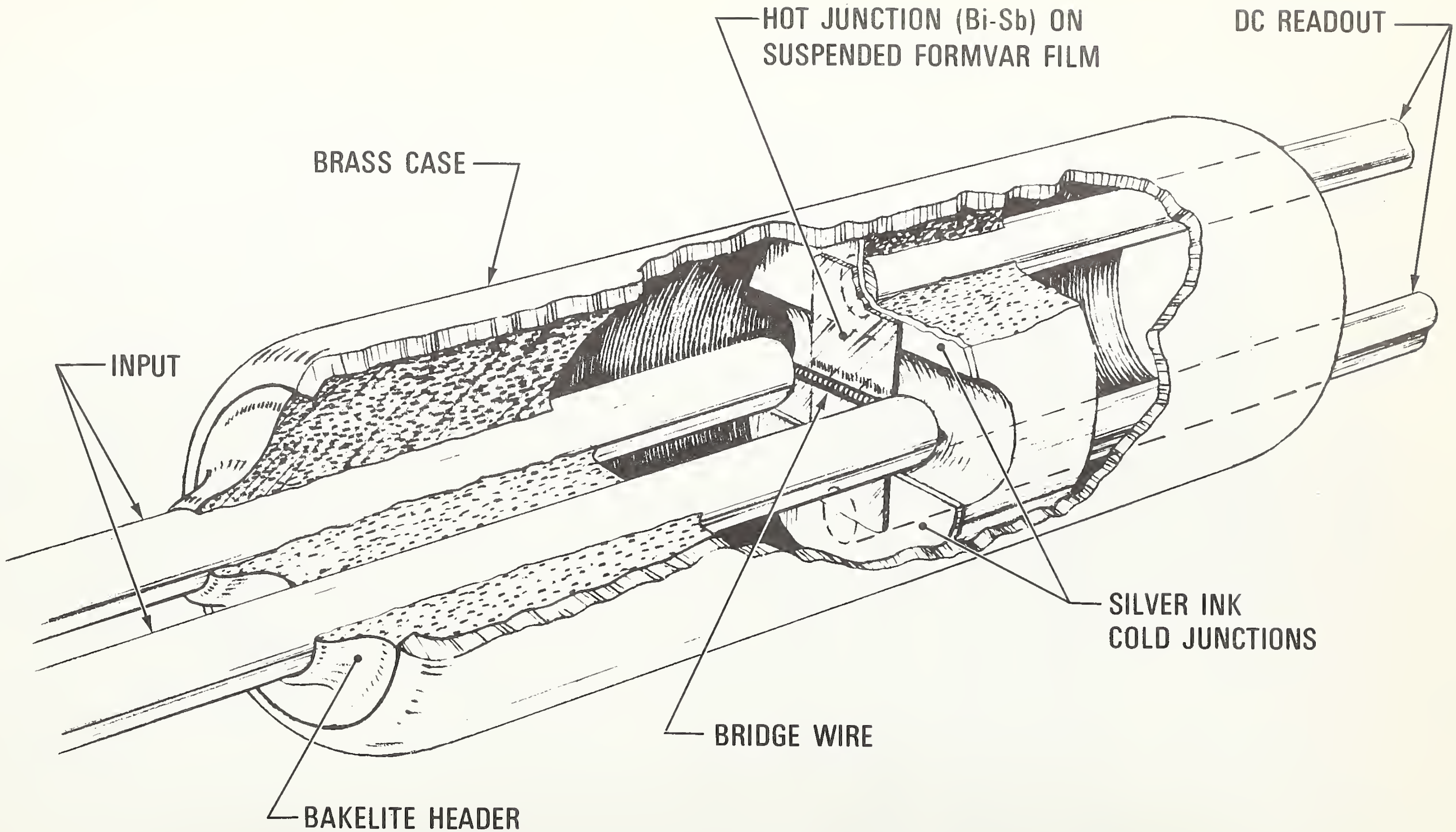


Figure 2. Details of the construction of the TCI-EED.

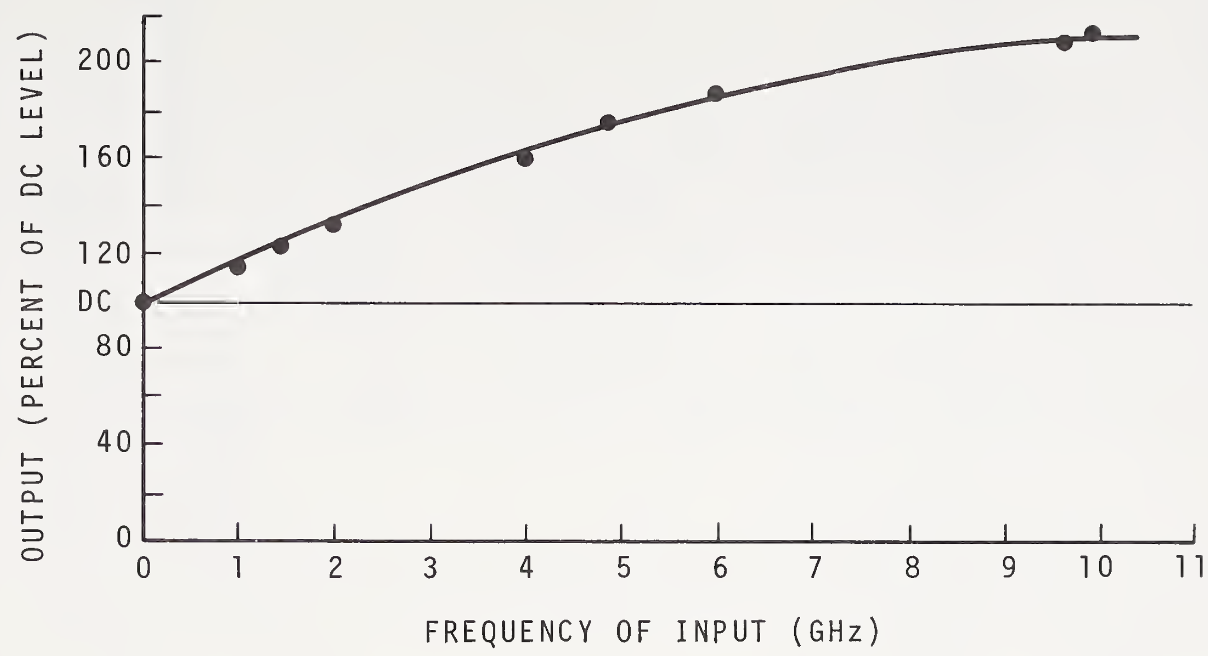
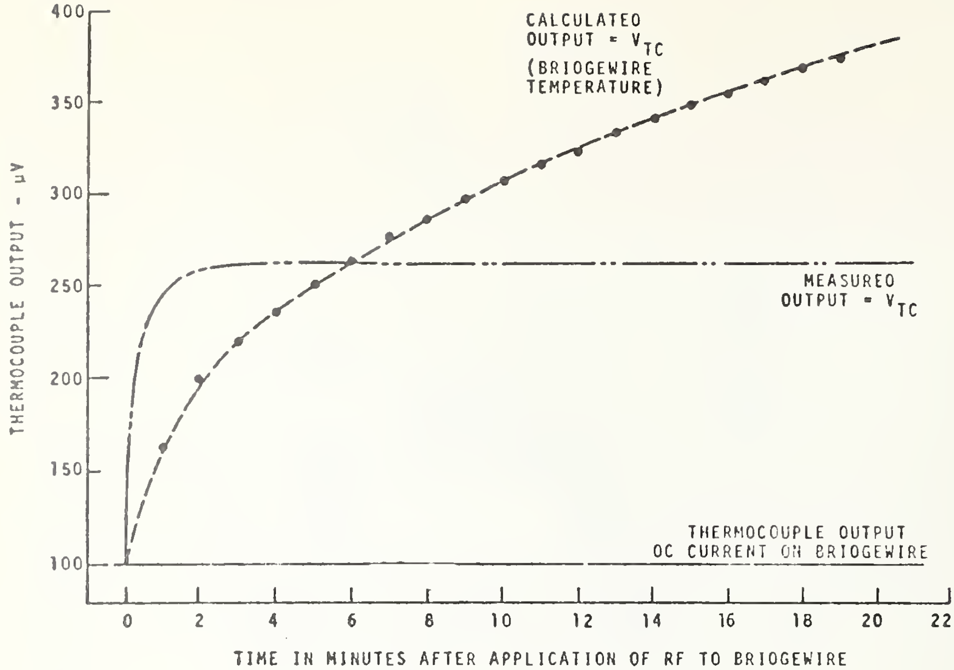
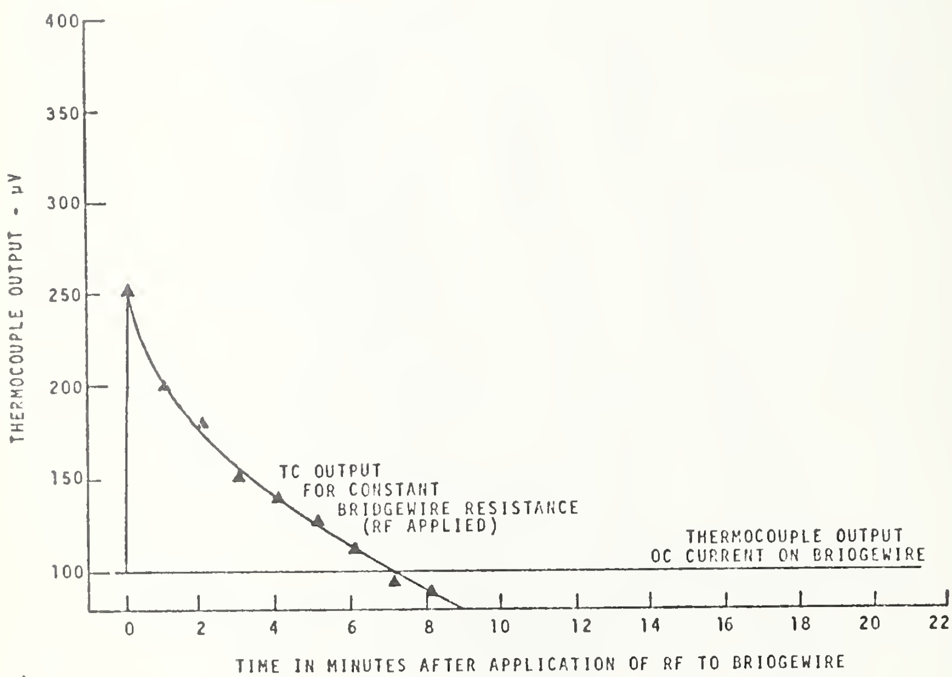


Figure 3. Output of TCI-EED as a function of frequency at constant bridgewire temperature.



a. Thermocouple output--constant rf power.



b. Thermocouple output--bridgewire temperature constant.

Figure 4. Thermocouple output characteristics with 10 GHz rf applied to bridgewire.

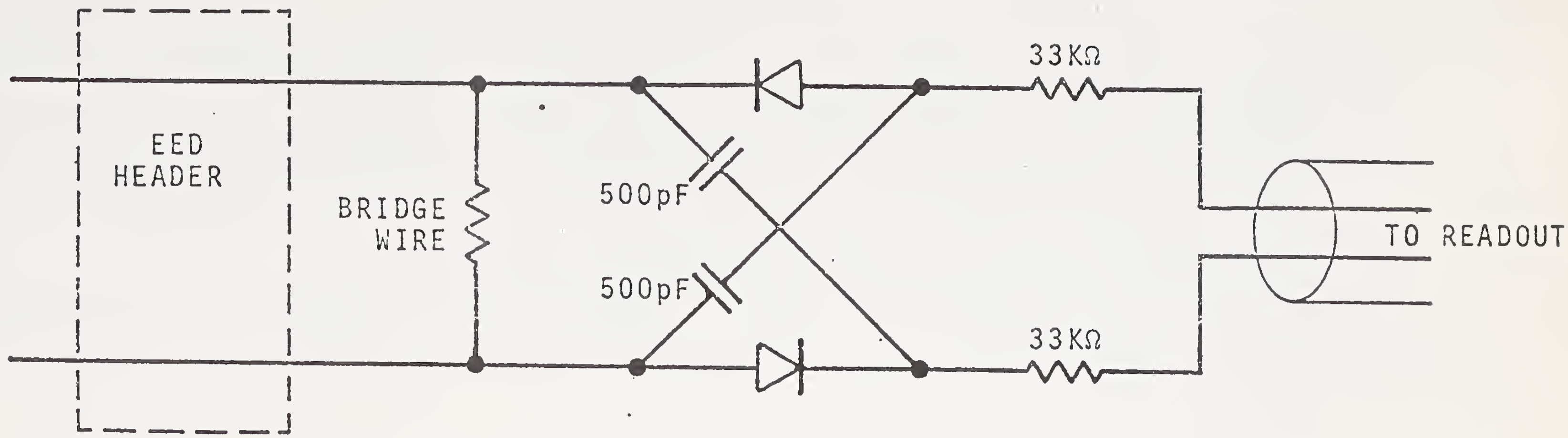


Figure 5. Video diode instrumented EED developed at Sandia Laboratories.

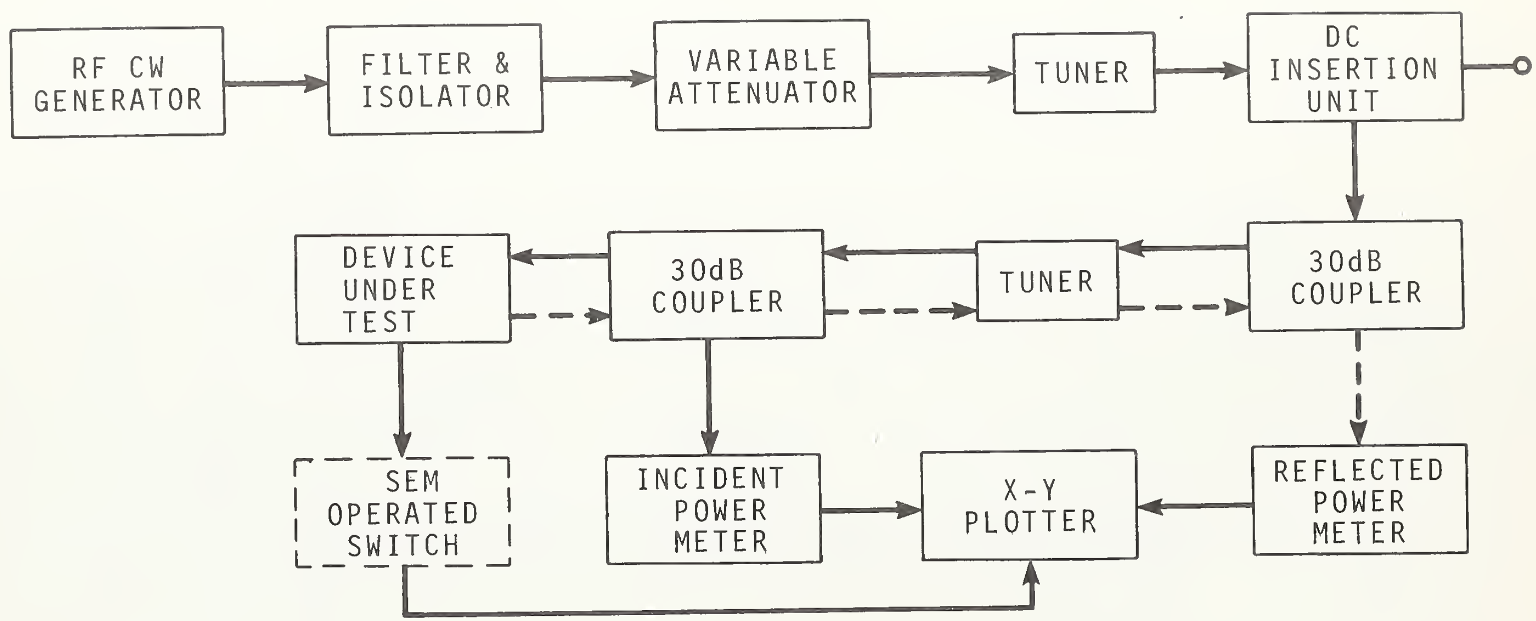


Figure 6. Block diagram of test setup for piston type SEM evaluation.

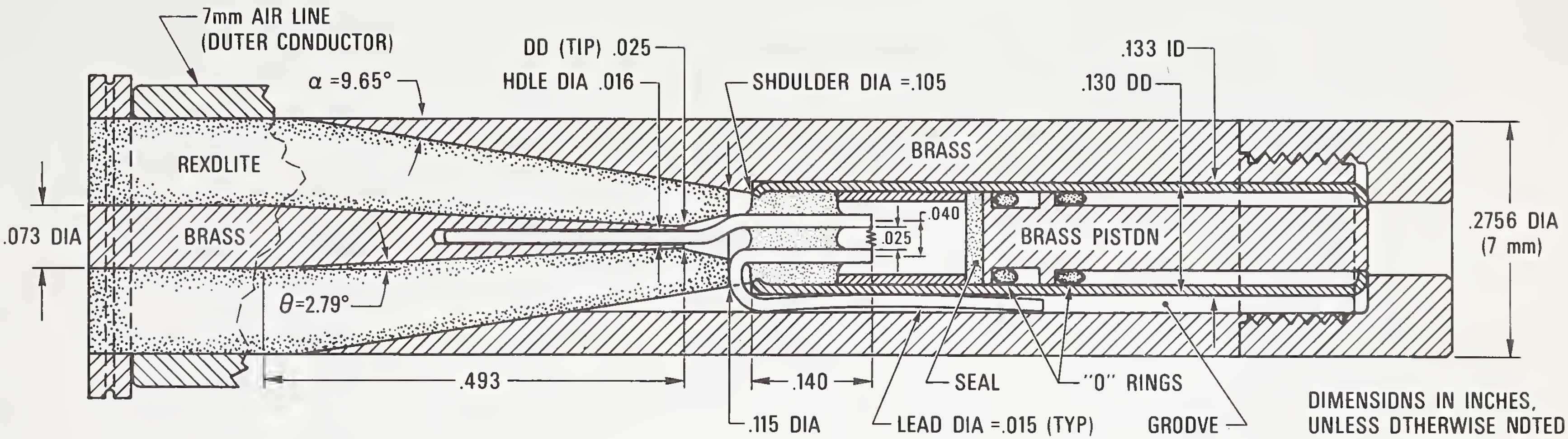


Figure 7. Section view of SEM in mount.

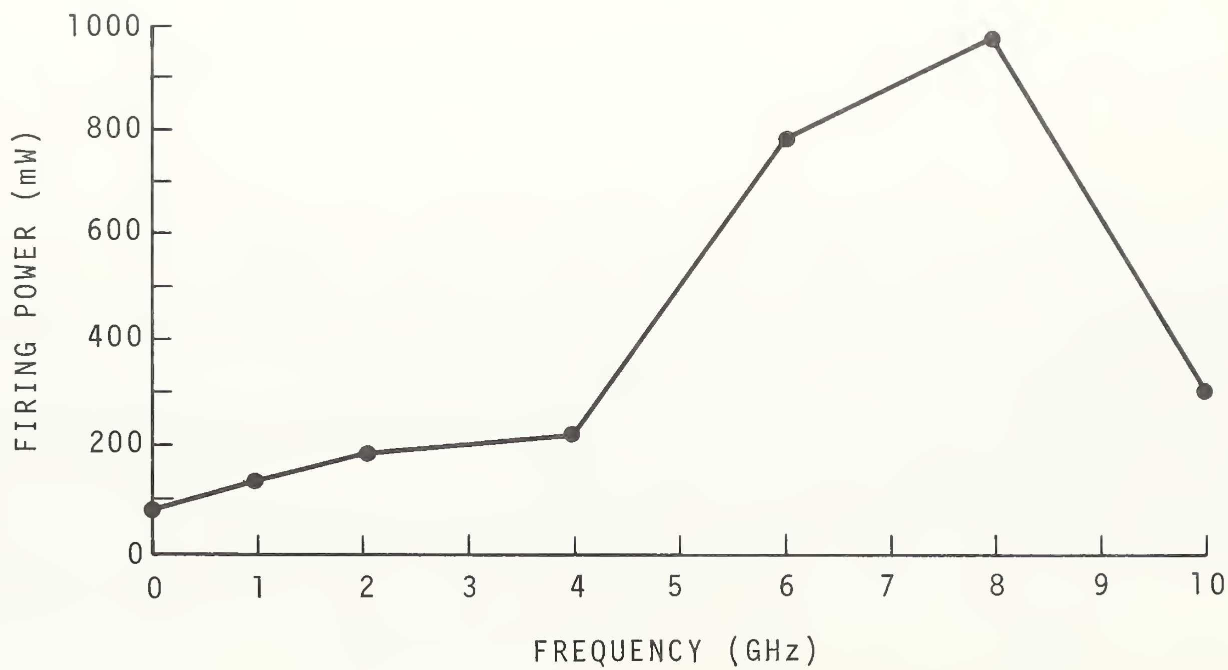


Figure 8. Average firing power of SEM's (piston-type) versus frequency.

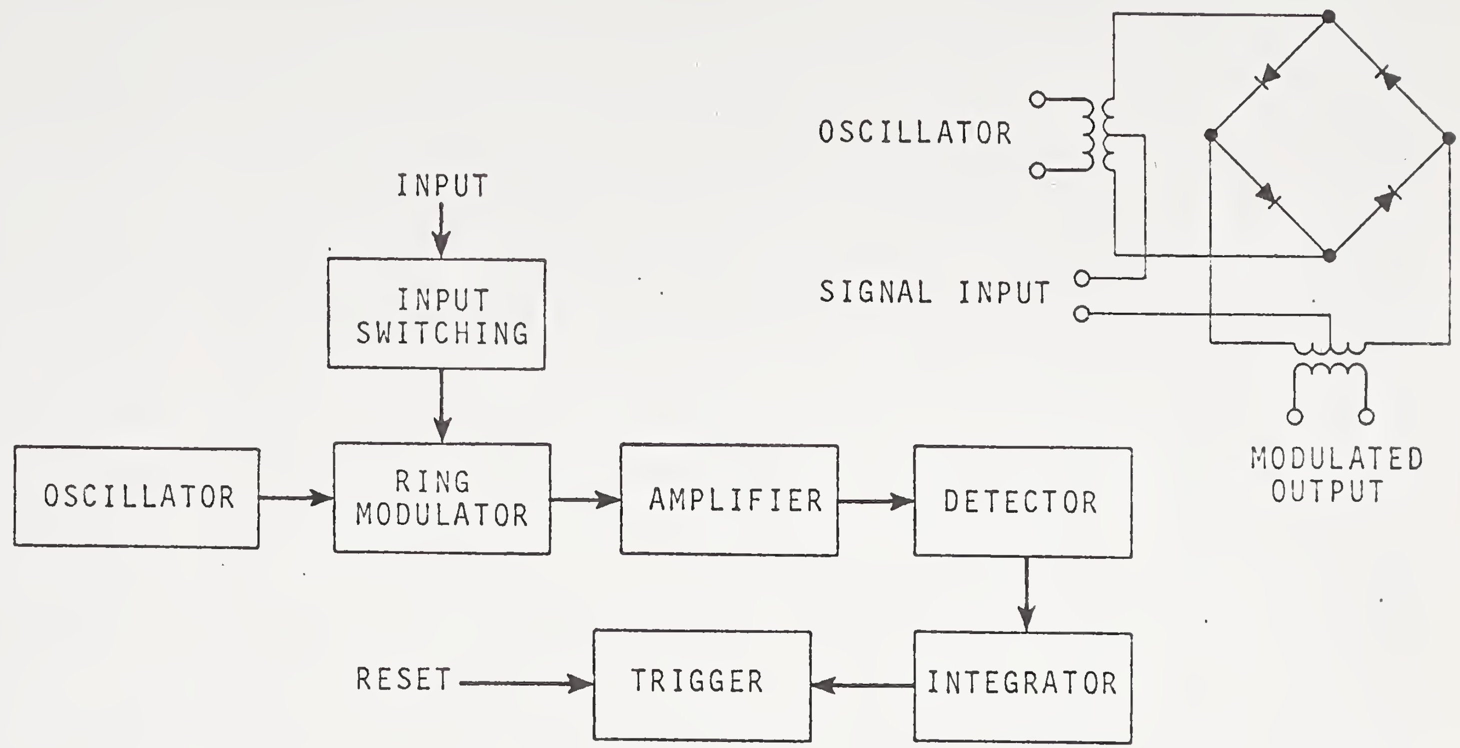


Figure 9. Ring modulator tester.

PHASE II

A NEW GO, NO-GO TYPE STRAY ENERGY MONITOR DEVICE FOR EED SAFETY QUALIFICATION

1. INTRODUCTION

There has been a long-standing need for a sensitive, broad-band, reliable, go, no-go type stray energy monitor (SEM) device in testing weapon and space systems for electro-explosive device(EED) safety. Such devices are required, for example, in routine pre-flight testing of aircraft prior to loading of ordnance. Other uses include in-flight testing of new or modified aircraft and to evaluate hazards of ground radars and other high power rf sources.

The term "stray energy monitor" refers in a broad sense to a class of devices which are used in safety qualification testing of systems. For the most part, these devices monitor power rather than energy. In practice, they are connected to the firing circuit in place of the actual EED's. Ideally, the SEM devices actuate at lower power levels than the EED's, which they replace and thus yield certain safety margins. These may differ depending on the situation. Where an accidental EED firing would be a hazard to life or cause extensive property damage, large safety margins (20 dB) are required. In less critical cases, lower margins may be allowed.

To conform with current usage in the literature, the terms pin and lead refer to one and the same thing. Pin may be thought of as that part of the input lead wire which lies inside the case while lead may be thought of as that part lying outside the case.

The normal firing mode of EED's occurs with the firing voltage connected pin-to-pin as shown in figure 1. These devices can also fire with accidental pins-to-case voltages (dc or rf) which may arc through the primary charge from pins-to-case. Thus, a suitable SEM device should monitor pins-to-case(p-c) voltage as well as pin-to-pin(p-p) power.

Other possible firing modes in EED's include heating of the header material due to dielectric losses and direct heating of the primary charge due to its dielectric loss in rf and microwave fields. These two modes have not been fully evaluated and the device described in this paper was not designed to monitor for accidental firing in these modes.

A description and evaluation of existing SEM devices and appropriate literature references are given in a companion paper[1]. Most of these devices were developed during the past fifteen years during which EED's came into large scale use in weapon and space systems. A brief summary of the various types and their performance characteristics are given here for comparison with the new SEM described in this paper.

Existing SEM's can be divided into two basic types, namely the go, no-go type and the quantitative type. The go, no-go type merely indicate that some power or energy threshold has been exceeded during test. Devices of this type include the piston actuator SEM which is similar to an EED in that it consists of a 2 ohm bridgewire and a small primary charge. When the primary charge detonates, a small, captive piston in the device ejects and indicates the fired condition. Unfortunately, the power sensitivity of the piston SEM varies from 0.08 W at dc to nearly 1 W at 8 GHz. Since typical EED's fire at approximately 1.3 W, the above sensitivity at 8 GHz provides very little safety margin. Required safety margins are of the order of 20 dB in accordance with MIL-E-6051D and hence the piston SEM is unsatisfactory at rf and microwave frequencies.

Another type of go, no-go SEM employs temperature sensitive paint which is applied to the bridgewire of a low power EED such as the Mark I. Following a test, the device is disassembled and the paint on the bridgewire is examined under a microscope. If the paint melted during a test, its texture will change from that prior to melt. Both the application of the paint to the bridgewire and the examination after test are tedious operations. In addition, judgment of the technician is required in determining whether the paint melted during a test. Because of the inconvenience in use, the temperature sensitive paint type SEM is considered marginal. It should be noted, however, that sensitivities of less than 10 mW have been reported in the literature[2].

A third go, no-go SEM is the so-called manganin gage[3]. It also employs temperature sensitive paint but on a tapered heater. The tapered heater allows estimation of the energy absorbed, rather than of power. Usefulness of this device is also considered marginal for the same reasons mentioned previously for the device employing paint on a bridgewire.

In addition to the deficiencies mentioned above, none of the present devices were designed to detect pins-to-case voltages. The present devices were therefore deemed inadequate to meet requirements established by the Air Force. The next step, then, was to develop a suitable SEM device and it is the purpose of this paper to describe its design and construction. It should be emphasized that the device described was designed to detect only those electrical hazards which heat the bridgewire or can cause arcing from pin-to-case.

2. DESIGN AND CONSTRUCTION OF NEW SEM

Prior to beginning the design of the new SEM, an analysis was made of the electromagnetic field configurations into and inside an EED. As shown in figure 1, the EED circuit consists of a pair of ungrounded leads which feed into the case through the header. The SEM is constructed in the same way. It is assumed that electromagnetic energy, which may be picked-up on the lead wires, is conducted into the EED(or SEM) through the input leads. The input leads may form a balanced pair of conductors(odd mode) and the EM field configuration inside the EED would be as shown in figure 2a. The leads can also form a parallel pair(even mode) with shield(case) return and the field pattern would be as shown in figure 2b.

A more likely occurrence is that an EM field excites both patterns simultaneously in some proportion. The resultant composite pattern is obtained by superimposing the modes. As can be seen, the EM fields at one of the pins(to case) is reduced and is enhanced at the other. With the proper phase and amplitude relationships, the p-c field at one pin could be zero. To cover this eventuality, the SEM is designed with a thin film fuse from each pin to the case.

The principal performance characteristics desired in designing the new SEM were the following.

1. Respond to both pin-to-pin power and pins-to-case voltage.
2. Power threshold in the 10 mW range for p-p voltages. Voltage threshold of 10 V for p-c hazards.
3. Flat sensitivity over the frequency range dc to 10 GHz.
4. Simulate electrical and thermal characteristics of typical EED's.

These characteristics were arrived at in consultation with the sponsor and were considered the design goals. The 10 mW power sensitivity was specified so as to yield a 20 dB safety factor relative to a 1 A, 1 W, no-fire EED. These employ a 1 ohm bridgewire.

Perhaps the most difficult design problem was that of obtaining threshold sensitivity in the 10 mW range. The only technique considered adequate to meet the sensitivity and flatness requirements and respond to power was a thin film fuse. Wire fuses of fractional mil diameters are available which will burn-out at approximately 10 mW. However, these have high resistivities(e.g., 10 kΩ/inch) and a relatively large inductive reactance at high frequencies. Since the bridgewire in typical 1 A, 1 W EED's is 1 ohm, a wire fuse satisfying both the 10 mW power threshold and the 1 ohm resistance could not be found.

Experiments at NBS showed that thin film fuses with burn-out power in the 20-30 mW range could be made. Even though the sensitivity is above the 10 mW design goal, it was nevertheless, considered adequate. The films are made by evaporation of a metal or metals which melt at a relatively low temperature. Metals tried included bismuth, indium and lead. Bismuth films provide a positive burn-out characteristic because the metal contracts on melting and clean break in the film occurs. Unfortunately, to deposit a 2 ohm resistance using bismuth, the film cross-sectional area is too great to provide the required power sensitivity for pin-to-pin monitoring. These films were found satisfactory, however, for the 2000 ohm fuse for pins-to-case monitoring where the threshold limit of 10 volts exists. This voltage sensitivity is more than adequate to detect arcing hazards since the breakdown of air occurs at approximately 75 V/mil. Spacing

for pins-to-case in typical EED's is of the order of 50 to 100 mils or more. Its relationship relative to adequate monitoring for dielectric heating of the primary charge is unknown at this time. This mode of firing in EED's has not been investigated adequately and it is not possible to estimate maximum allowable voltages.

The development of a suitable 2 ohm film with sharp burn-out characteristics and low power sensitivity proved to be a difficult task. First trials were made with indium films because this metal has relatively high conductivity and melts at 428 K(155°C). The 2 ohm indium units melted at approximately 15 mW of absorbed power. Unfortunately, molten indium wets many materials including the thin polyimide substrate onto which the films were deposited. Thus, upon melting, the film resistance undergoes a step function to a higher value (e.g., 3 ohm to 8 ohm) but continues to conduct. Upon cooling, the resistance returns to near its original 2 ohm value. The indium films could be burned out by increasing the power to 65 mW but this level is somewhat higher than desired.

Several alloys with low melting temperatures were tried such as indium-bismuth, indium-tin, and lead-bismuth. In some cases the resistivity of the alloys was high which required a very thick film to yield the 2 ohm resistance. With the indium alloys, the films tended to behave like pure indium. The indium-tin films began to burn-out at 30 mW but several seconds were required for completion.

With the failure to produce suitable 2 ohm films with alloys, it was decided to experiment with pure, low temperature melting metals other than indium. Lead and tin films were made and tested and it was found that tin films, made as shown in figure 3, would burn-out at 25 to 30 mW. This

power level is higher than the design goal but, due to a lack of time for further development it was decided to use tin for the 2 ohm p-p fuse.

Both the 2000 ohm, p-c, bismuth films and the 2 ohm p-p, tin film are deposited on a single 0.25 mm (0.001") thick polyimide substrate. The contact pads are made by depositing 0.010 μm (100 Å) chromium onto the polyimide followed by 0.05 μm (500 Å) gold at a substrate temperature of 523K (250°C). Following deposition of the tin and/or bismuth films, an additional 0.5 μm (5000 Å) deposition of gold was made onto the pad area and the total fuse heated to 423K (150°C). In fabricating prototype units, 6 units were deposited at one time through a mask onto a 25 mm X 25 mm (1" X 1") polyimide substrate. The fuse strips were then cut from the large substrate.

The lay-out for attaching the film fuses to the header pins is shown in figure 4. The gold epoxy is first applied to the fuse pads and the pads were then pressed against the pins. Firing at 393K (120°C) for 45 minutes completes the bonding process.

An exploded view of the complete SEM device is shown in figure 5. To insure good contact between the two outer pins and the case, the case is bonded to the header with conductive epoxy cement which must be cured at 65°C for 3 hours.

Because the SEM case is bonded to the header with epoxy, the SEM cannot be disassembled to detect fuse burn-out by visual means. Therefore, a small test box was developed which gives positive indication for burn-out of the 2 ohm p-p fuse or either of the 2000 ohm p-c fuses. A selector switch on the box allows a separate check for each mode and burn-out is indicated when the appropriate red light glows.

The circuit is powered by 4 type A dry cells and can easily be held in one hand. Use of the test box is simple and straightforward and little operator instruction should be required. A diagram of the circuit is shown in figure 6 and a photograph of the prototype model is shown in figure 7.

3. PERFORMANCE CHARACTERISTICS

Measurements to determine the rf performance characteristics of the new SEM device were made using equipment as shown in figure 8. The tuned reflectometer allows measurement of the net power (P_n) absorbed by the SEM to within about 5 percent. The X-Y recorder is arranged to measure incident power (P_i) on the Y-axis and reflected power (P_r) on the X-axis. Net power is $P_n = P_i - P_r$. The instant at which burn-out occurs is easily determined because the sudden change in P_r causes the recorder trace to change slope abruptly.

The coaxial mount used to hold the SEM during tests is a special design employing a 7 mm coaxial line. Its description and construction details are given in the companion paper[1]. The mount is below resonance at frequencies up to at least 10 GHz and, therefore, it does not absorb appreciable power. In measuring the burn-out power of the 2 ohm p-p fuses, it was necessary to connect one of the SEM leads to ground in the 50 ohm, unbalanced, coaxial system as shown in figure 9a. The ground lead in effect shorts one of the p-c fuses for dc and low frequency signals, but not generally for high rf and microwave frequencies. The equivalent circuit, which should be valid from dc to fairly high frequencies, is shown in figure 9b. The inductance, L, is due to the 7 mm length of lead between the fuse and the point where the lead is connected to the outer conductor. The resultant field

pattern inside the SEM is probably similar to some superposition of the basic odd and even modes.

Earlier, it was mentioned that the burn-out power for the 2 ohm p-p tin fuse was 25 to 30 mW. This is the burn-out power when the 2 ohm fuse alone is mounted in the header. When the two 2000 ohm p-c fuses are added, with the pin connection as shown in figure 9, they absorb additional power. This fact can be appreciated by referring again to figure 9b, where it can be seen that at high frequencies, current in the 2 ohm leg of the circuit tends to flow through the 2K ohm resistor rather than through L. The net result is that with the addition of the p-c fuses, the net input power required to burn-out the 2 ohm fuse increases with frequency. An analysis of the equivalent circuit showed that 3 times as much power is required to burn-out the 2 ohm fuse at about 10 GHz than at dc. Results of tests, shown in figure 10, tended to verify this. Net power to the SEM required to burn-out the 2 ohm p-p fuse was 30 mW at dc and increased to 90 mW at 10 GHz. This is a decided improvement over prior SEM's where up to 800 mW of rf power is required for response of the device. This loss in sensitivity is the price paid for adding the capability to test for hazardous p-c voltages.

The degree to which the fuse-type SEM simulates the electrical characteristics of typical EED's is considered adequate. The 1 ohm resistance of EED bridgewires is adequately simulated by the 2 ohm p-p fuse. While EED's are open-circuited pins-to-case, the 2000 ohms resistance of the p-c fuses in the SEM is not believed a critical degrading compromise with respect to simulating an EED.

4. SUMMARY

Presently available go, no-go type stray energy monitor devices (SEM's) used for EED safety qualification testing are relatively insensitive at rf and microwave frequencies and do not provide monitoring for hazardous pins-to-case voltages. A new SEM employing thin film fuses as the sensitive elements has been developed at the National Bureau of Standards. The pin-to-pin fuse burns out at 30 to 90 mW at frequencies from dc to 10 GHz respectively. Also, pins-to-case monitoring from each pin is provided at a threshold level of 10 V. These sensitivities are believed adequate for testing of hazards to accidental firing of 1 A, 1 W EED's in the two modes described.

A small, hand-held test box was constructed which gives positive indication of burn-out for any of the 3 fuses when the SEM is connected to it after a test.

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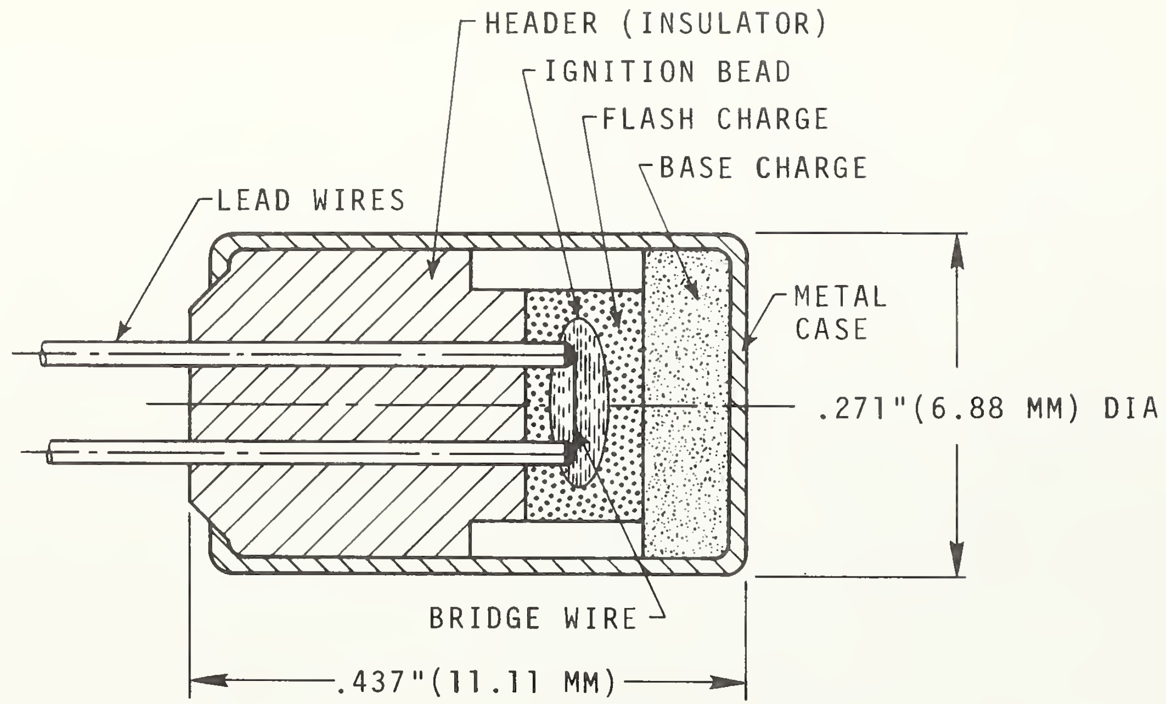


Figure 1. Section view of typical electroexplosive device(EED).

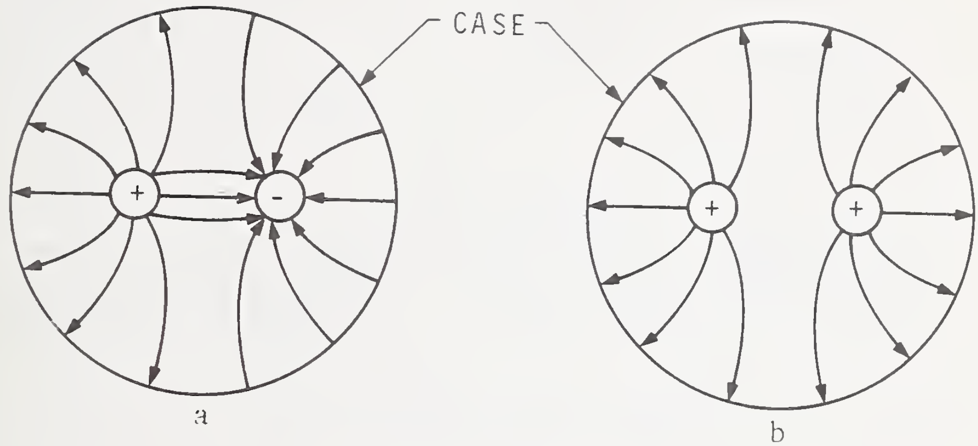


Figure 2. Field configurations in two-conductor shielded transmission line
a. Balanced (odd mode)
b. Parallel (even mode)

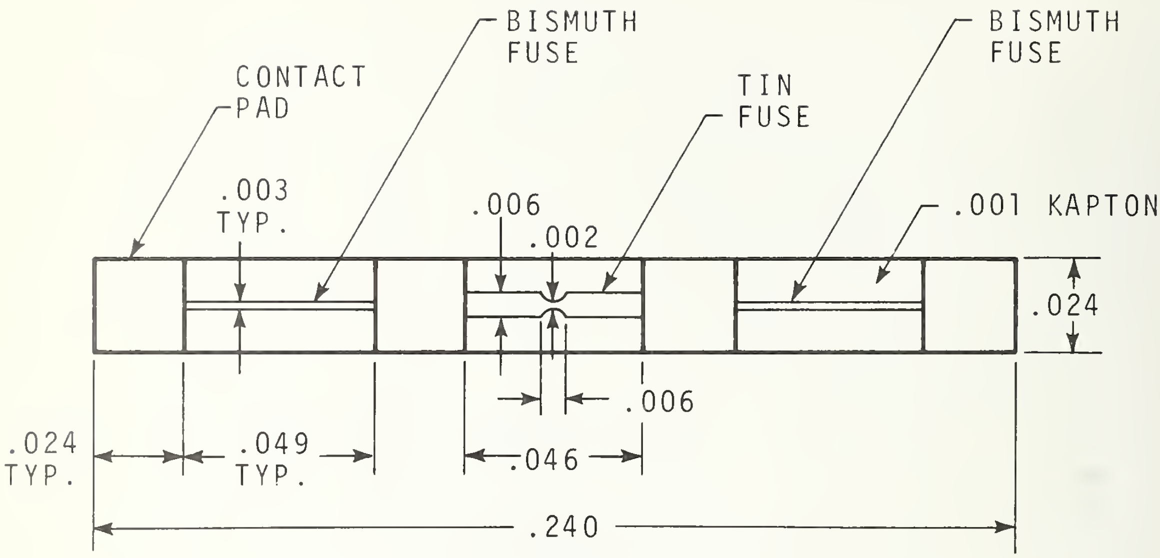


Figure 3. Dimensions of thin film fuses.

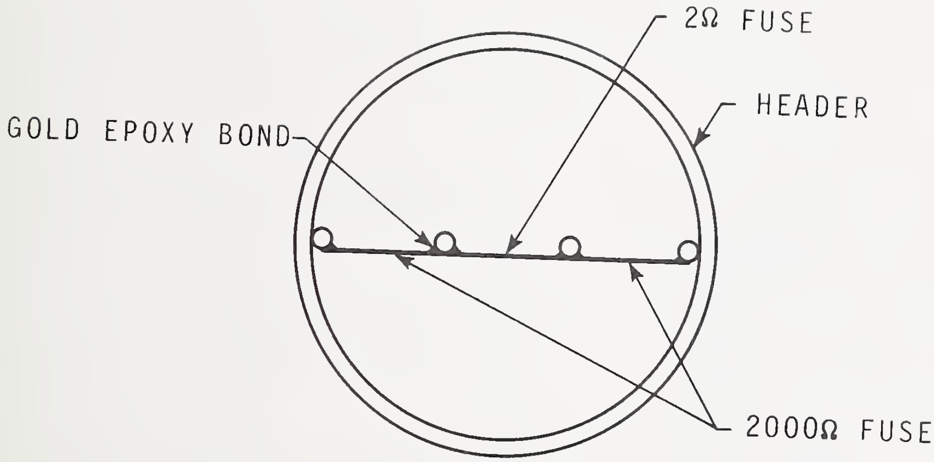


Figure 4. Arrangement of fuses for attachment to pins-header assembly.

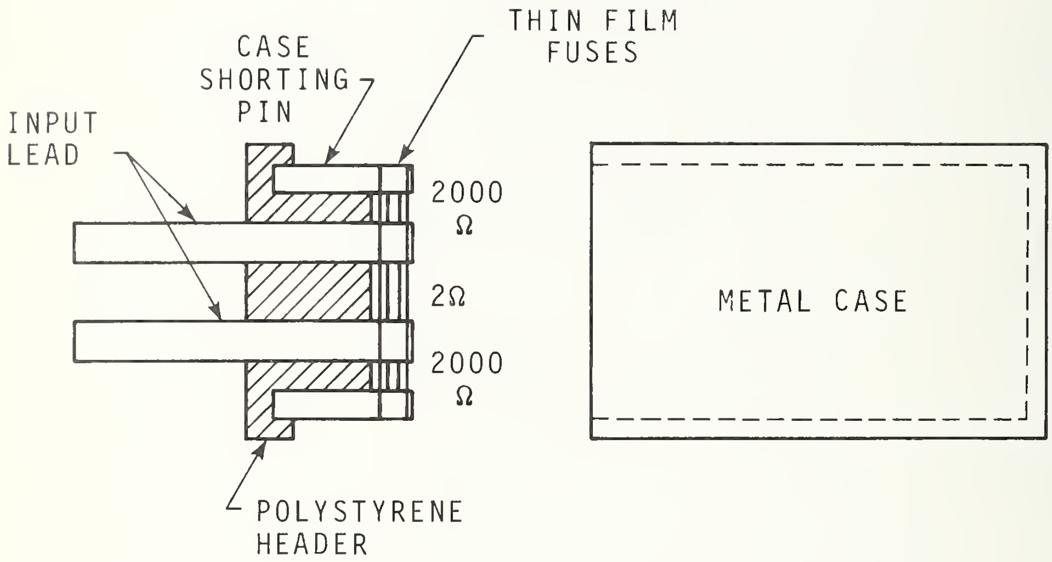
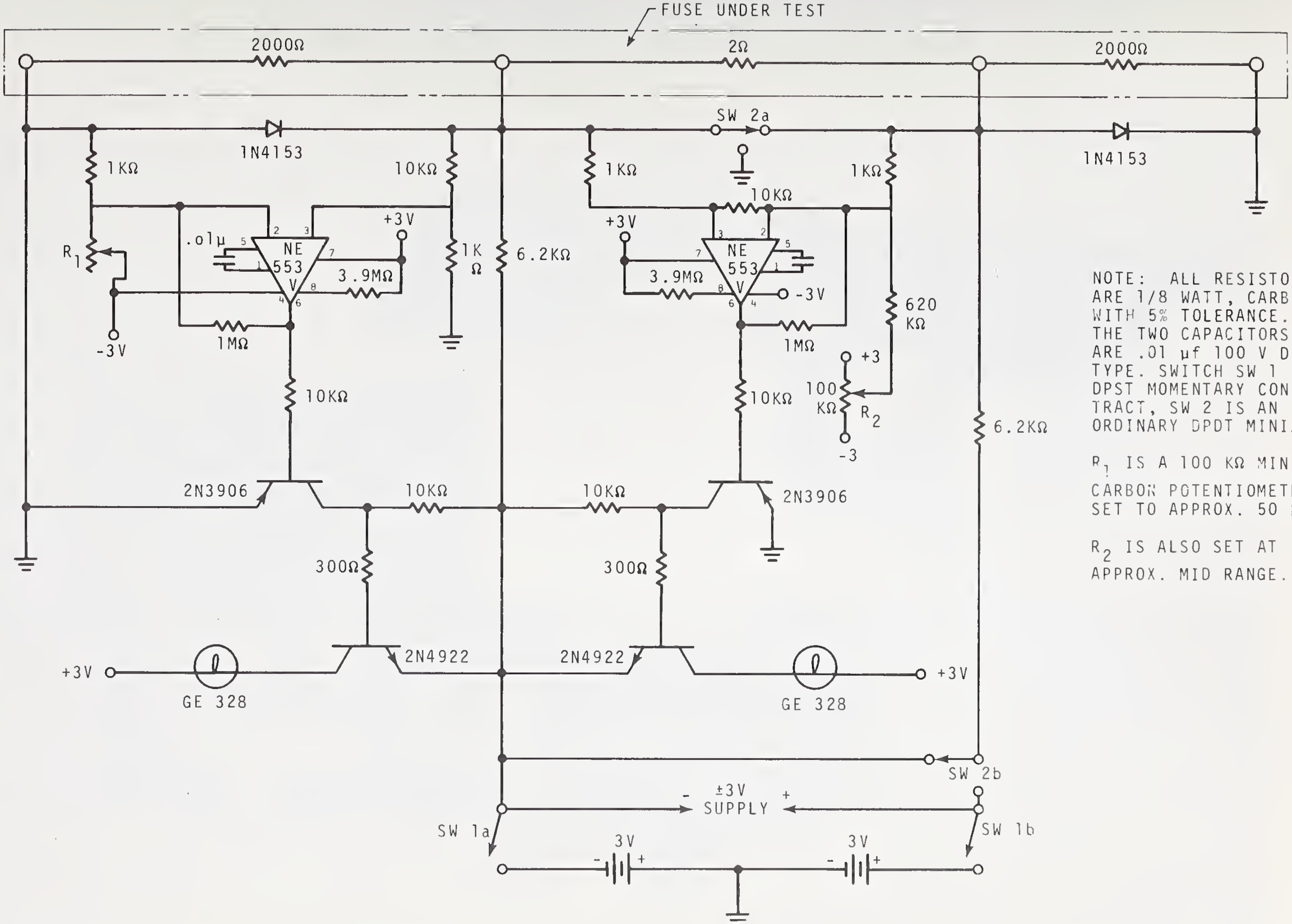


Figure 5. Exploded view of complete SEM device.



NOTE: ALL RESISTORS ARE 1/8 WATT, CARBON WITH 5% TOLERANCE. THE TWO CAPACITORS ARE .01 μf 100 V DISC TYPE. SWITCH SW 1 IS DPST MOMENTARY CONTACT, SW 2 IS AN ORDINARY DPDT MINIATURE.

R_1 IS A 100 KΩ MIN. CARBON POTENTIOMETER SET TO APPROX. 50 KΩ.

R_2 IS ALSO SET AT APPROX. MID RANGE.

Figure 6. Circuit diagram of prototype SEM test box.

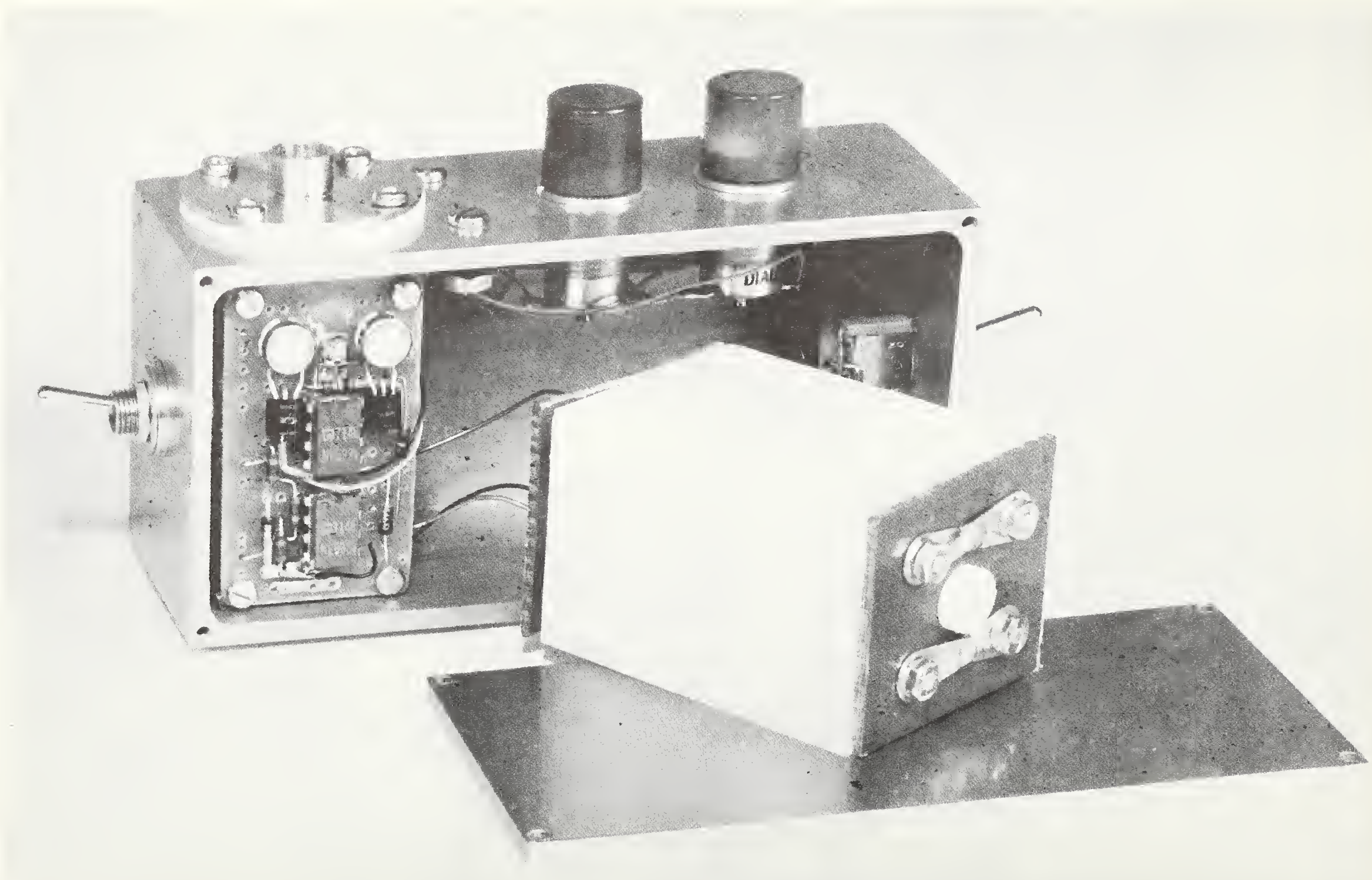


Figure 7. Photograph of prototype SEM test box.

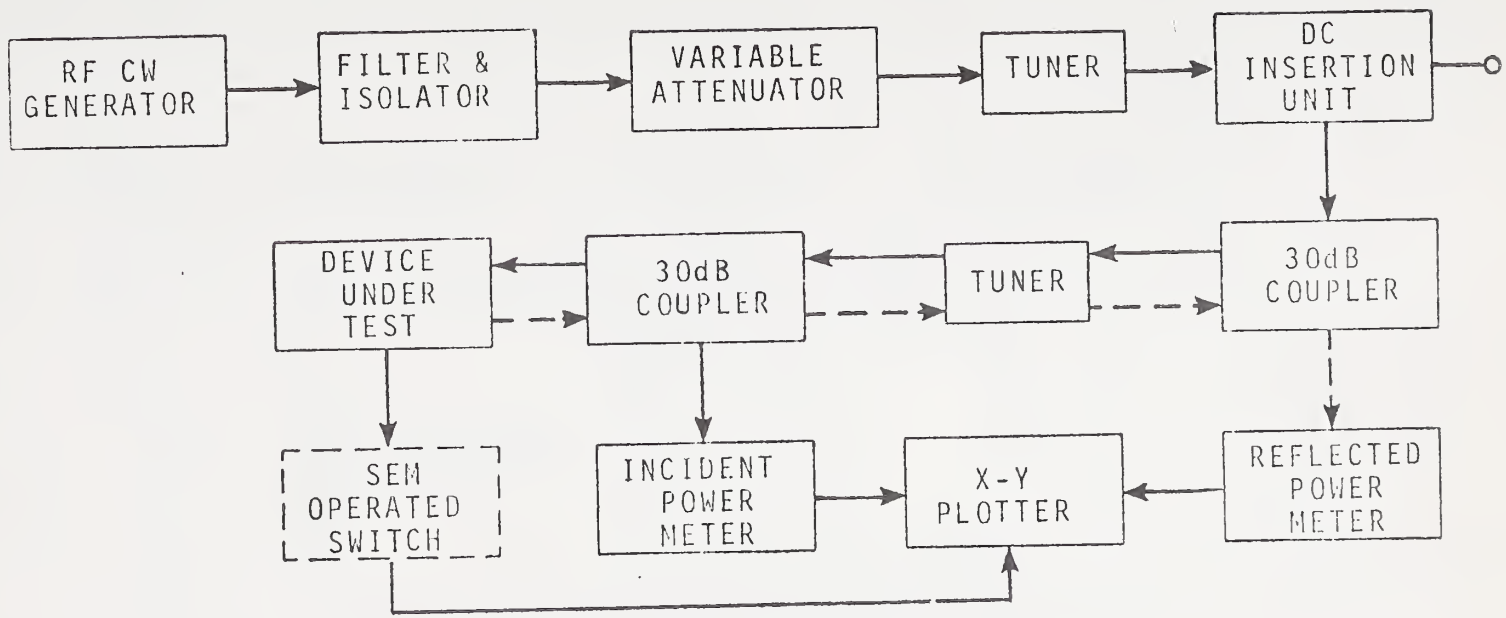


Figure 8. Block diagram of SEM test setup.

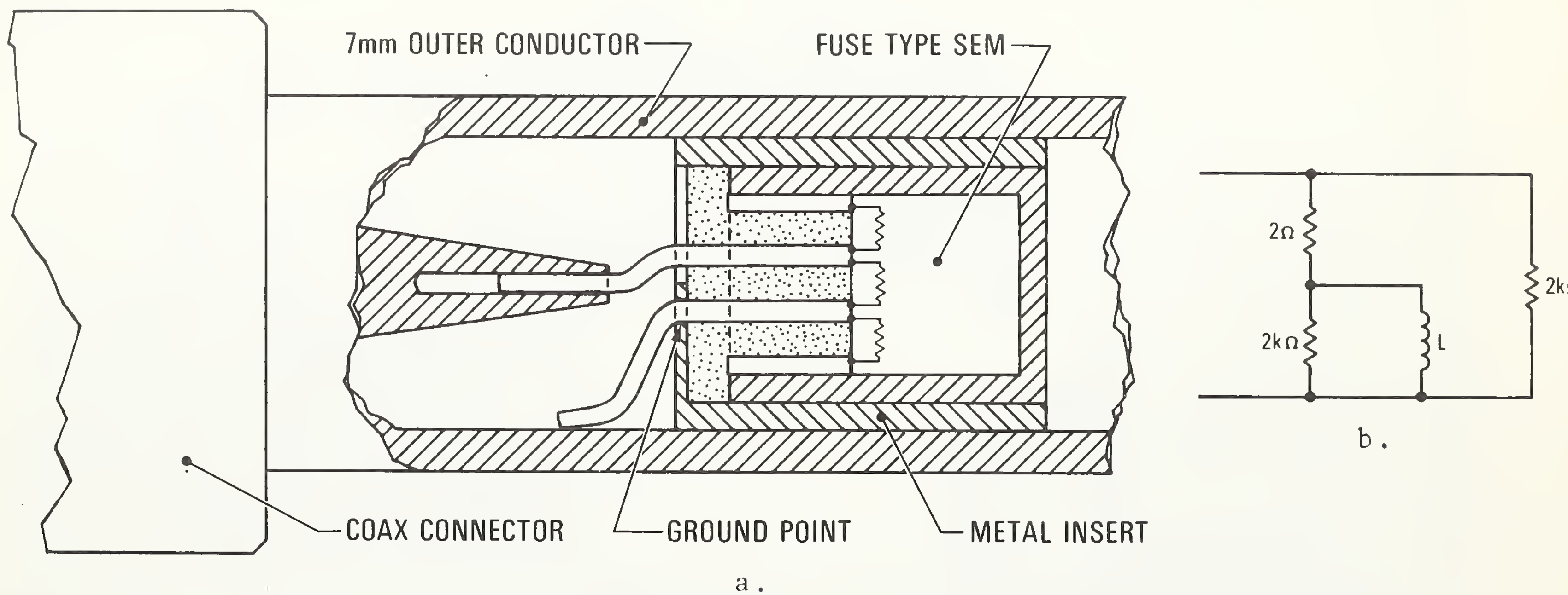


Figure 9. a. Method for connecting SEM to coax mount.
b. Equivalent circuit.

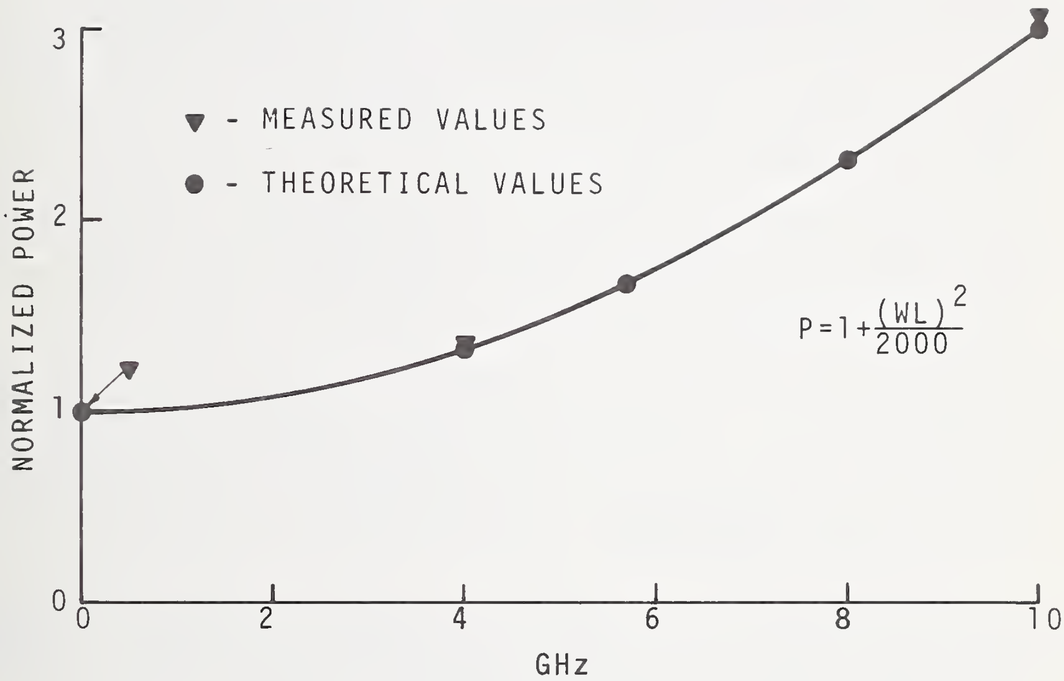


Figure 10. Burn-out characteristics versus frequency for fuse type SEM.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Adequate qualification of weapon systems for EED safety has been a long-standing problem in the military services. During the past 15 years various instrumentation, test devices, and methods have been developed with some success. In this report, available devices and instrumentation are evaluated with respect to sensitivity to low power levels, broadband response, ease of use, etc. This work is included in Phase I of the program.

In Phase II the objective was to develop a new go, no-go type stray energy monitor (SEM) with sensitivity in the tens of milliwatts range and response up to at least 10 GHz. A description is given of the new SEM which employs thin film fuses and monitors both pin-to-pin and pins-to-case hazardous voltages. Safety factors obtainable with the new device are in the 15 dB range relative to a 1 A, 1 W EED.

17. KEY WORDS (Alphabetical order, separated by semicolons)
Electroexplosive device safety; electromagnetic compatibility; electromagnetic interference; squib.

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